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Yamal LNG Project: Searching for Optimal Number of Carriers

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Preface

The thesis process has been completed under the guidance of supervisor Associate Professor Bjørnar Aas, and I would like to start with sincerely thanking him for providing professional guidance and valuable critique, comments and advices during the course of the thesis. My profound gratitude also goes to Research PhD of Economics and Associate professor Studenikina Ludmila at Russian Gubkin State University of Oil and Gas, who has been an important contributor of remarks, discussions and suggestions throughout the research process, and has also served as a link to the company.

Thanks to the all members of my team from Gubkin University for their patience and command spirit during the hard work together during this progect.

I would also like to express gratitude to Logistics Managers from «YAMAL LNG» which served as contact persons for their time and readiness to provide information. I am truly thankful for the opportunity to write a thesis and thereby acquire further knowledge about the fascinating industry of seaway transportations.

Finally, a special thanks to my family. Mom and Dad you have encourage me all my study to keep going and pursue my dreams. Many thanks also to my brother Eugeny for his thoughts and good willingness.

Summary

The main aim of this thesis is to find an optimal logistic scheme for gas shipments from Yamal Peninsula to Europe. Hard climate and ice conditions make this problem not as trivial as in other tanker projects

The problem can be summarized as a number of LNG-Tankers that need for transportation of LNG from "Yamal LNG" to Zeebrugge. What we want to summarize speed and capacity of tankers, ice conditions on the route and seasonal specify to find optimal number of vessels.

As result of imitation model replications we found an optimal number of vessels for Sabetta – Zeebrugge route/

KEYWORDS: LNG, IMITATION MODEL, ARCTIC TANKERS,
ICE CONDITIONS, OPTIMMAL NUMBER OF VESSELS.

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1 Introduction

The growth of global demand in oil and gas resources and the depletion of hydrocarbon reserved in traditional production regions are key drivers in moving gas industry to the Arctic region.

Global warming make Northern Sea Route (NSR) more perspective transport route for oil and gas logistics. This route can be used for hydrocarbons transpotration to Europe and perspectively to Far East.

It is planning in 2017 to start of Yamal LNG plant. All its production will be exported by sea route. We can estimate perspectives of new route of gas supplyment.

The purpose of this paper is finding of optimal number of LNG carriers for this project based capacities of LNG plant and vessels and geographical conditions.

The simulation package Arena by Rockwell Software Inc. was chosen to develop the simulation model. This product has been used by well-known organizations worldwide as a support tool for their decision-making process.

The remainder of this thesis is divided into eight parts. Section 2 presents the basic definition of Global LNG Industry. Section 3 reviews the LNG life cycle. Section 4 describes the Northern Sea Riute. Details of Yamal LNG project are listed in Section 5. Section 6 focused on ice conditions in Russian Arctic. Section 7 describes the simulation model employed in this thesis. Data collection, assumptions and limitation are defined. The simulation procedure and model is explained in detail. Section 8 describes the experiments and their results with interpretations. Section 9 concludes the thesis by summarizing the study’s findings and by identifying recommendations for future research.

2. The LNG Industry

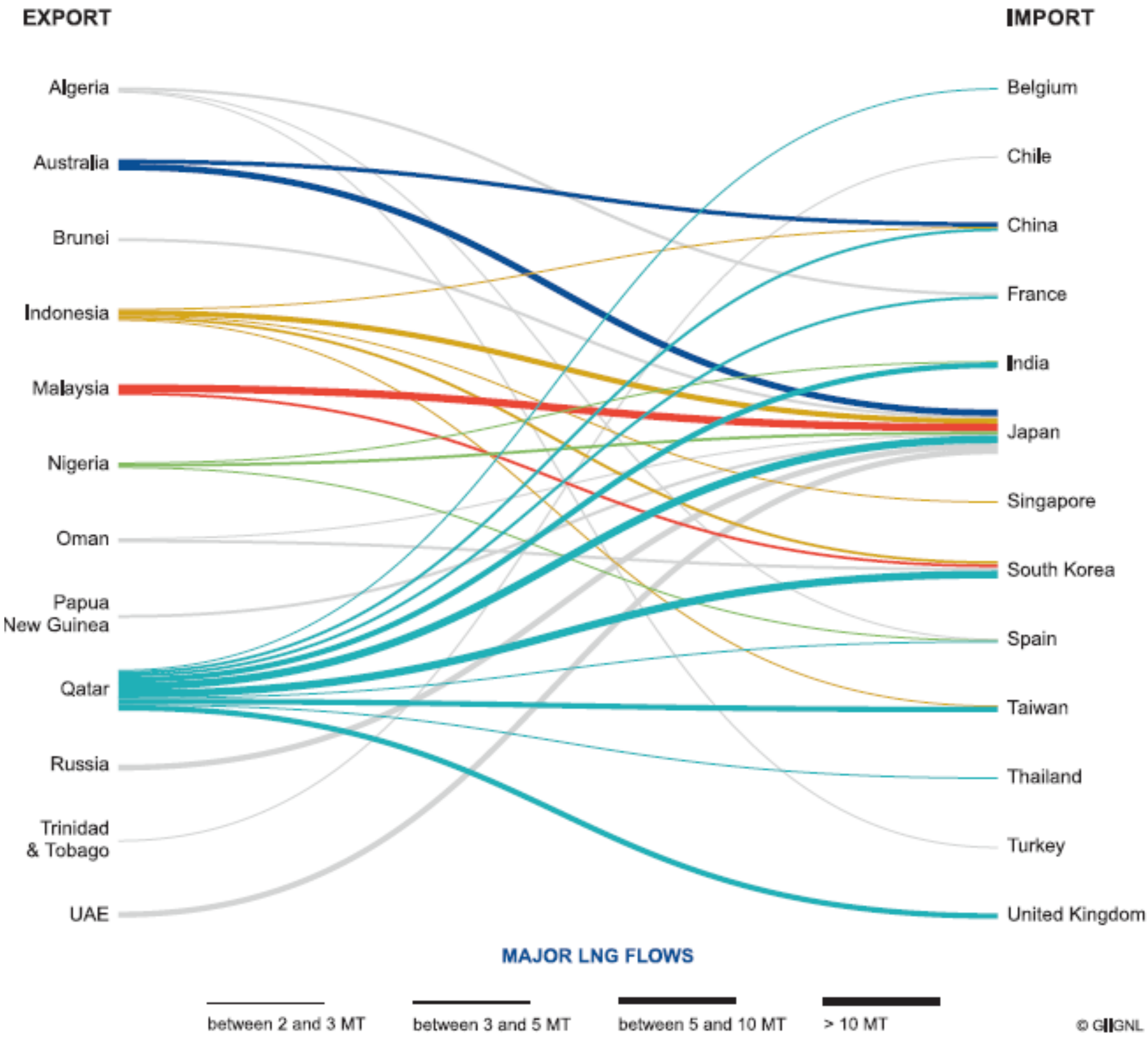
2.1 Global LNG industry

The LNG industry appeared in 1964, when the first contract for the supply of LNG from Algeria to Great Britain and France was concluded. For 50 years, annual sales of LNG increased 110-fold: from 3 billion to about 331 billion cubic meters. According to the International Group of Liquefied Natural Gas Importers, GIIGNL, in 2015, LNG imports in the world reached 245.2 million tons, with 72% of global LNG consumption coming from Asia (GIIGNL, 2017).

Natural gas provides about a quarter of the world's energy consumption, of which 10% belongs to LNG. The LNG industry is developing more rapidly than any other branch of the energy sector - its capacity is increasing by about 7% per year (IGUa, 2015). According to the International Energy Agency (IEA) by 2030 the LNG sector will become the locomotive of the globalization of the gas industry. For example, if the volume of pipeline deliveries of natural gas has increased by 45% over the past 10 years, then LNG sales have more than doubled.

The main LNG exporters are 19 countries. Qatar remains the leader, which occupies about a third of the market. Large enough LNG facilities are located in Malaysia, Australia, Nigeria, Indonesia, Trinidad and Tobago, Algeria, Russia. A number of large capacity LNG plants are being built in Australia, two of them commissioned in 2015 (GIIGNL, 2017). Experts predict the leadership in the industry to this country by 2018 (IGUa, 2015). A large number of LNG projects besides Australia in the next ten years are also planned to be implemented in the US, Russia and Canada. The development of shale gas production in the United States leads to an excess supply in the domestic market, thereby stimulating the export of LNG.

Figure 1: LNG export and import flows by country in 2015. Source: GIIGNL, 2016[1].

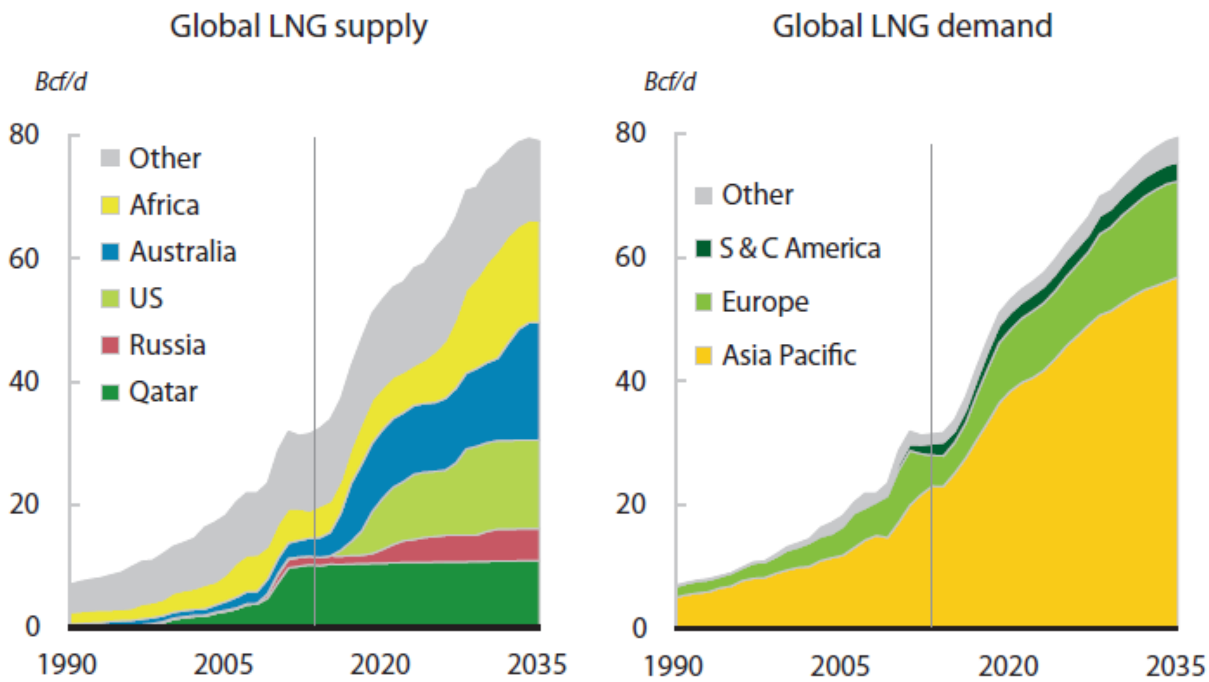


Currently, LNG imports are in the state of 34 countries that have the appropriate infrastructure for receiving LNG. The main importers are the countries of the Asia-Pacific region (Japan, South Korea, China, India, Taiwan), Europe and South America, the USA. The import of LNG to Europe is consistently declining. In 2015, it was less than 16%, while in 2011 this figure was twice as high in absolute values (GIIGNL, 2017). This is due to both the large use of alternative energy sources in Europe and the economic crisis that leads to less energy consumption. It is noteworthy that with a general decrease in gas consumption in the European Union, the share of LNG in

[1] GIIGNL Annual Report http://www.giignl.org/sites/default/files/PUBLIC_AREA/Publications/giignl_2017_annual_report_0.pdf

imports is increasing. It is obvious that LNG pulls on itself a part of consumers, which before that have traditionally been supplied with pipeline gas, including Russian ones.

Figure 2: Worldwide LNG supply/demand balance forecast. Source: BP Energy Outlook 2035[2]



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Shell expects that for the period 2015-2030. The global LNG market will grow by 84% (an approximate growth of 5% annually - from 250 million tons to 460 million tonnes). Such a dynamic increase in the consumption of liquefied natural gas is due to a number of factors:

- the growing needs of China in clean energy sources;
- the need to form new energy producing capacities in Latin America and Southeast Asia (SEA);
- an increase in household consumption of LNG in the Middle East and Europe[3].

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[2] BP Energy Outlook 2035 http://www.bp.com/content/dam/bp/pdf/energy-economics/energy-outlook-2016/bp-energy-outlook-2016.pdf

[3] Shell LNG Outlook http://www.shell.com/energy-and-innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook/_jcr_content/par/textimage_1374226056.stream/1488553856456/88c077c844a609e05eae56198aa1f92d35b6a33cc624cf8e4650a0a6b93c9dfb/shell-lng-outlook-2017-overview.pdf

The global LNG shipping fleet consisted of 410 vessels as of January 2016, with a total capacity of 60 mmcm. The 28 LNG vessels delivered in 2015 far outweighed the shipping requirements from the additional 4.7 MT of incremental LNG trade, exacerbating the oversupply in the LNG shipping market and leading charter rates to fall 49% between January and December 2015.

2.2 Russian Oil and Gas Industry

According to British Petroleum review – Russia is among the world's the largest producers and exporters of oil and gas (BP 2015b). Annual natural gas production has been about 600 billion cubic metres during the last 20 years. 30% of this exported westward via the pipeline system. In 2009, Russia opened its first LNG plant on Sakhalin in the Okhotsk Sea; since 2010 it has produced and exported between 20 and 26 million cubic metres of LNG, equal to some 12 to 16 billion cubic metres of dry natural gas, to the Asia-Pacific region (BP 2015b). Since 2000, Russian oil production is growing: in 2010, it exceeded 500 million tons per year and by 2014 had reached almost 527 million tons.

Between 140 and 260 million tons per year, or about half of the oil produced in Russia, has been exported as crude since 2000; in addition, the country exported between 62 and 152 million tons of refined products. Since 2005, annual export of liquid hydrocarbons from Russia has exceeded 350 million tons (Gazprom Neft 2016).

More than 90% of the oil and gas produced in Russia is transported by trunk pipelines of the state-owned Transneft and Gazprom. The largest gas producer, Gazprom, has a monopoly on dry natural gas export and delivers gas through the Unified Gas Supply System to domestic and foreign customers. Transneft pipes crude oil and products for export using onshore grid and seaport terminals at the Baltic, Black, Azov and Okhotsk Seas, with the largest terminal being Primorsk at the Baltic Sea. Russian Baltic port terminals tranship more than 100 million tons of oil and products annually (133 million tons in 2014), receiving cargo by both trunk pipelines and railways.

2.3 Arctic Shipping of Oil and Gas

According to Rosstat and Russian Customs data Russian oil shipping for export along the Arctic coast had insignificant volumes before the beginning of 2000s. In 2002, there was a sharp increase in petroleum cargo flow, with over 5 million tons going to Western Europe via the Barents Sea. In 2003, those volumes increased to 8 million, and to 12 million tons in 2004. Each year after 2004, sea-going tankers have delivered between 9 and 15 million tons of Russian crude oil, products and gas condensate for export from terminals in the Kara, White, Pechora and Barents Seas. Most of this resources went westwards to Rotterdam. From 2010, petroleum cargo has also been exported eastwards through the Northern Sea Route (NSR). In 2013, 650 thousand tons of liquid gas products, including 67 thousand tons of LNG from Statoil's Melkøya in the Norwegian Barents Sea, were delivered to Asian markets through the NSR (NSR IO 2014).

Over the past 15 years, terminals in the Russian Arctic for offloading crude oil, gas condensate and refined products for export have been developed and overall shipping capacity has been enlarged. There have been some relative decreases in shipping volumes, but these have been due to various external factors, e.g. changes in export taxes and railway rates, construction of new trunk pipelines and ports in the Baltic and Far East, bankruptcy of key actors, rather than lack of capacity or logistics problems in utilising the potentials of Arctic terminals. Altogether, 20 terminals of various types and scales along the Arctic coast from Tiksi in the east to the North Cape in the west have been used to offload Russian crude oil, refined products and gas condensate for export, with more to come.

3 LNG Lifecycle

The life cycle of LNG begins when natural gas enters the liquefaction plant. The LNG plant carries out the preparation and liquefaction of gas, after which LNG arrives for storage in special tanks. Shipment of LNG is carried out on tanker-gas carriers. Tankers further deliver LNG to LNG receiving terminals that are equipped with storage tanks and regasification facilities. In these plants, LNG is converted to a gaseous state and delivered to consumers. LNG can also be delivered to consumers and in a liquefied condition, in road tankers, tank containers or tank wagons by rail. The LNG life cycle is presented here for large-scale production, from which LNG delivery is carried out by sea by large-capacity tankers (the most capacious way of transporting cryogenic cargoes).

3.1 Liquefaction

The feed gas supplied to the natural gas liquefaction complex is a mixture of gaseous hydrocarbons (including methane, ethane, propane, butane, etc.), hydrogen sulfide and other gases. This gas must be prepared for liquefaction, as much as possible after being cleaned of impurities and drained. Each technological line of the plant is equipped with an installation for the removal of acid gases (carbon dioxide CO2 and hydrogen sulfide H2S), dehydration of gas with molecular sieves, a mercury removal unit using activated carbon, a fractionation unit for separating propane and ethane and producing a stable condensate, For liquefying gas. The liquefaction of natural gas, which, after purification and drying, is predominantly methane, is produced in a series of cryogenic heat exchangers, which ensure the sequential cooling of the gas to -161.6 ° C. The plant for the production of liquefied natural gas is essentially like a huge refrigerator that produces cooling and converting ordinary natural gas (pre-cleaned) into a liquid state. The least energy-intensive such enterprises in climatic conditions, characterized by low temperatures, for example, in the Arctic.

Compared with the preparation of natural gas intended for gas pipeline transportation, gas purification for subsequent liquefaction is carried out more carefully. This is necessary to prevent the freezing of associated impurities, damage and clogging of refrigeration equipment in the cryogenic sections of the plant.

The flare plant of the LNG plant is an integral part of the industrial safety system, both during normal process flow and in abnormal situations, for example, when the power is turned off or the equipment fails. Flare combustion is the process of rapid and safe removal of flammable gas from process units and pipelines through a high vertical pipe, followed by burning on a burner. During the operation of the plant, the burner located at the top of the flare pipe is constantly maintained in the lighted state, which indicates normal operation

The LNG produced on the process lines enters special storage tanks. LNG is stored in a cooled form under pressure, slightly larger than atmospheric pressure. Tanks usually have a cylindrical shape with spherical bottoms. The level of daily evaporation (the so-called boiling-off gas, BOG), that is, the percentage of the amount of LNG evaporated per day and the maximum LNG volume that can be stored in the reservoir ranges from 0.05 to 4%, depending on Reservoir design (API, 2015). Evaporated gas is removed from the tanks in order to maintain constant pressure and is used as fuel in turbogenerators at the plant.

3.2 Storage

Storage tanks for LNG are made with double walls: the outer wall is designed to delay LNG vapor, and around the inner wall there is a thermal insulation system. Tanks are made of metals or alloys with a low coefficient of thermal expansion, which do not become brittle when in contact with cryogenic fluids (in particular, they are made of aluminum or steel with 9% nickel content). Around the modern LNG storage tanks, mounds or dumps are built, designed to contain liquid leaks of any volume, namely up to 110% of the volume of the corresponding reservoir. Sometimes in the design of LNG tanks an external container of prestressed reinforced concrete is used, which can contain the contents of the inner reservoir in case of leakage from it.

3.3 Marine Transportation

In the world at the moment the most widespread are marine LNG shipments in special tankers-gas carriers. Shipment of LNG to tankers is carried out from the quay equipped with hoses (stowers) - shipping and for boiling-off gas. LNG is pumped from storage tanks in the loading line leading to the LNG landing berth. At the head of the berth, the pipelines are connected to the berths of the berth, and those in turn - with cargo tanks of gas carriers. The duration of loading operations varies from 6 to 16 hours, depending on the cargo capacity of the vessel. The LNG tanker is a vessel for transporting LNG from liquefaction and storage facilities to consumers. Structurally, modern LNG tankers have several contributing spherical or prismatic cargo tanks, or built-in membrane-type tanks. In the event of an accident, LNG tankers have a two-hull design specifically designed to prevent leaks and ruptures. In the event of damage to the primary reservoir, the secondary shell should not allow leakage. All surfaces in contact with LNG are made of materials that can withstand extremely low temperatures. All types of cargo tanks also have powerful thermal protection, which, however, does not prevent the heating of tank walls due to the difference in ambient temperatures and transported LNG.

The latter, in turn, causes boiling of LNG and its transition from the liquid phase to the gaseous (boiling-off gas). Typically, during the voyage of a tanker tanker in cargo tanks a day, a boiling-off gas is produced in quantities of 0.1% (when ballasted) to 0.15% (when the tanker is loaded into cargo) of the total LNG volume (API, 2015). Thus, with a tanker capacity of 170,000 m3 of LNG, 170-255 m3 of boiling-off gas is generated daily.

On LNG tankers with a bi-fuel (diesel and LNG) engine or with steam turbines, the boiling-off gas is used as a marine fuel. Excess gas is collected by a vapor recuperation system, re-liquefied and returned in a liquefied form to cargo tanks. If there is no liquefaction system for the boiling-off gas on the tanker, it can be burned in a gas combustion unit (GCU). During loading operations, the intensity of generation of the boiling-off gas can increase by a factor of 1.5-2 times, while the internal gas consumption of the tanker in stand-by mode can be approximately 10% of this volume (Afon and Ervin, 2008). Excess boiling-off gas is diverted to a special hose at the LNG shipment terminal and further to the shore re-liquefaction system or can be burned in a gas combustion device (GCU).

3.4 Regasification Terminals

LNG is unloaded at the acceptance terminals through a network of pipelines to storage tanks and regasification plants. LNG storage tanks at the design acceptance terminals are similar to those in LNG plants, but they are more numerous at the LNG acceptance terminals, since it is necessary to have a reservoir stock taking into account the uneven supply and shipment of the product. In regasification plants, a controlled LNG evaporation process takes place, and then natural gas is sent to distributors and end users via pipelines. If consumers need LNG, they are reloaded into tank trucks or tank wagons and transported by road or rail, respectively.

4. The Northern Sea Route

4.1 Territory of Northern Sea Route

The Northern Sea Route (NSR) in accordance with the Federal Law "On Inner Sea Waters, the Territorial Sea and the Contiguous Zone of the Russian Federation" (1998) is defined as "the historically established national unified transport communication of the Russian Federation in The Arctic"[4]. The internal connection of the Arctic zone of Russia is not high due to the rare network of cities, the high cost of air and land transport and poorly developed infrastructure.

NSR is almost 2 times shorter than other marine routes from Europe to the Far East. The length of the main ice route of the Northern Sea Route from Novaya Zemlya Straits to the port of Provideniya is 5,610 km; The length of navigable river routes adjacent to the NSR is about 37,000 km. However, a long and harsh winter with a short cold summer conditions the great ice cover of the Arctic seas, are the main obstacle for passage of ships on significant sections of the route. The most difficult conditions of navigation are formed in areas of large accumulations of heavy ice, which are not completely destroyed even in the warmest months (Taimyr and Ionian ice massifs). The transportation of transports is possible only with the help of icebreakers.

NSR is an important part of the infrastructure of the economic complex of the Far North and a link between the Russian Far East and the western regions of the country. It unites the largest river arteries of Siberia, overland, air and pipeline types of transport into a single transport network. For some areas of the Arctic zone - Chukotka, the islands of the Arctic seas and a number of settlements on the coast of the Taimyr (Dolgano-Nenets) Autonomous Okrug - sea transport is the only means of transporting goods and livelihood of the population. On the direction of Murmansk-Dudinka, a year-round navigation is carried out to ensure the activities of the Norilsk Mining and Metallurgical Combine (NMMC).

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[4] Federal Law "On Inner Sea Waters, the Territorial Sea and the Contiguous Zone of the Russian Federation" (1998) http://ivo.garant.ru/#/document/12112602:0 http://base.garant.ru/70207760/

Figure 3: Scheme of the Northern Sea Route

4.2 Perspectives of Northern Sea Route

Interest to the Northern Sea Route is determined by two major factors. First of all, it can become more profitable from an eco-nomic point of view as an alternative to the current transportations between the ports of Europe, the Far East and North America. For this route, for example, from Hamburg to Yokohama, only 6,600 nautical miles, while through the Suez Canal -11,400 miles.

On the other hand, the Northern Sea Route is interesting as a transport artery for transportation of mineral raw materials from the Arctic regions of Russia. In the surrounding areas, 35% of the world's oil and gas reserves are contained. Transports of Russian gas and oil by sea can be more profitable than the construction and operation of gas and oil pipelines. In addition, along the Northern Sea Route, it is possible to arrange the transport of mineral fertilizers from the Kola Peninsula to East Asia and China.

In 2010, the traditional trans-shipment of cargoes of Norilsk Nickel, the Ob Bay and the North Shipment was accompanied by trans-shipment in an easterly direction. This is the transfer of petroleum products to Chukotka, the export of hydrocarbons from Murmansk to China and the transit of iron ore concentrate from Norway to China. The potential volume of shipments through the NSR may amount to 38 million tons per year. And foreign experts predict that by 2020, the volume of transit to the east will increase to 6 million tons, and in the west - 3 million tons per year.

Together with the issues of development of the Arctic resources of the Arctic, the issues of transport security for the enterprises that master it arise. If, for example, the Polar Urals ore can still be delivered to the consumer bypass routes with large transport costs, then the Yakutia or Chukotka ore can only be delivered to the consumer by the NSR. Since there are no railways in the north of Siberia.

The dynamics of the growth in the number of icebreakers and transport vessels, the development of port transport and technological complexes and maritime safety management systems will be determined by the pace of economic activity in the Arctic zone and the growth of the freight base for the NSR.

4.3 Northern Sea Route and Arctic Natural Resources

The prospective volumes of transshipment in the Northern Sea Route will be related to the development of oil and gas deposits on the Yamal peninsula, the basins of the Ob and Yenisei rivers, as well as in the adjacent areas of the Barents Sea (the Timan-Pechora oil and gas province, the Shtokman gas condensate and the Prirazlomnoye oil field And others) and the development of the sea export of oil and gas from these deposits to Europe. The export of non-ferrous metals, produced by the Norilsk Mining and Metallurgical Company, will somewhat revive. The appearance of a new Arctic shipping route is the Belushya Bay - the port of Murmansk, associated with the development of a large polymetallic deposit (with geological reserves of 10 million tons for metal) and manganese ore deposits (3 billion tons) on Novaya Zemlya.

The incentive for the development of navigation in the eastern part of the NSR may be the export of rare earths and apatites from the Arctic Tomtor field in the Republic of Sakha (Yakutia) and the polymetallic deposits from the deposits in Chukotka to the countries of the Asia-Pacific region. With direct government support, commercial forestry enterprises will be able to develop in the basins of the Yenisei and Lena rivers and the export of timber cargo via the NSR will resume. There is a real opportunity to increase the volume of transit traffic through the NSR due to the export of ferrous metals and mineral fertilizers produced by exporting enterprises in the European part of Russia. As the economy of the Arctic zone revives, the volume of cabotage traffic will increase by the NSR.

According to the forecast estimate, the total volume of shipments in the NSR in 2018 will reach 14-15 million tons, including: the export of oil, liquefied gases and gas condensate from the Timan-Pechora and Ob-Yenisei deposits will increase to 8-10 million tons; Transit cargo transportation - up to 2.5 million tons, including export of Russian fertilizers and metals; Export of timber cargo from the basins of the Yenisei and Lena rivers - up to 1 million tons; The volumes of coastal shipping and northern deliveries will also increase.

A possible direction of NSR development can be the formation of an international company that can promote the development of a transit international transport corridor, in the improvement of its work many countries of the world are interested.

These plans have serious obstacles. First, the underdevelopment of the infrastructure of the NSR, especially its eastern part. The second problem is competition from the southern routes. For swimming in Arctic waters, ice-class vessels are required, and they are significantly more expensive than conventional ones, and specially trained teams are also needed. In addition, drifting ice and unfavorable weather conditions can make it difficult for the vessel to move in arctic waters even during ice-free navigation. Finally, transport companies in prince are very conservative in terms of choice of routes. Any new routes are new risks, and they increase the cost of insurance.

5. Yamal LNG

5.1 Goals and Participants

The project "Yamal LNG" includes the construction of a large-scale integrated natural gas liquefaction complex (LNG) with projected production capacity from 15.0 to 16.5 million tons of liquefied natural gas per year, as well as production facilities with a capacity of 1 Million tons of gas condensate per year. The production base is the resources of the South Tambey gas condensate field (STGKF). The project provides for the extraction, processing, liquefaction and shipment / export of natural gas and stabilized condensate from the project area on the Yamal Peninsula (Russian Federation).

Figure 4: Map of the Yamal-Nenets Autonomous Okrug and Project Location

The project will include a network of facilities, including drilling sites, gas collection, preparation and liquefaction facilities, LNG storage and shipping facilities, a seaport (including a preparatory port for receiving materials required during the construction phase), an airport, as well as facilities Life support infrastructure for personnel and other auxiliary facilities. The LNG production facility (LNG plant) will consist of three production lines for the production of liquefied gas with an annual capacity of 5.0-5.5 million tons each; Their phased commissioning is scheduled for 2016, 2017 and 2018 respectively. The maximum volume of production of stabilized gas condensate is 1 million tons per year.

The STGKF is located in the north-eastern part of the Yamal Peninsula, 540 km northeast of the city of Salekhard, the administrative center of the Yamal-Nenets Autonomous District. STGKF is part of the Tambey Group of deposits, which also includes the East Tambey, North Tambey and Tasia deposits.

The shareholders of Yamal LNG are:
- Novatek OJSC is the largest independent producer of natural gas in Russia engaged in the exploration, production, processing and sale of natural gas and liquid hydrocarbons;
- Total Exploration & Production (is a subsidiary of the international energy concern Total, whose activities include exploration, prospecting drilling and production of natural and liquefied gas;
-The Chinese National Oil and Gas Corporation (CNPC).

5.2 Project Infrastructure

The Project will include the following main infrastructure objects:
• Gas gathering (including condensate) network, including a network of production wells and prefabricated gas pipelines;
• Gas preparation facilities and methanol production unit (for preparation before liquefaction);
• Power plant with a capacity of 376 MW;
• LNG plant, including 3 process lines;

• LNG and condensate reservoirs;

• Port facilities of the preparatory period (berths for unloading construction materials and materials during the construction period) and the main operation period for shipping LNG and condensate to sea transport (the operator will be a third party).

• The airport, mainly for transportation of working personnel;

• Auxiliary engineering networks and facilities in the form of local roads, bridges (for transitions through water objects), overhead power lines, workshops, etc .;

• Complex of facilities for staff accommodation.

The project will be serviced by a unified system of engineering and technical support networks located in the technical zones allocated for this purpose. This will reduce the required areas and bring networks close to buildings and structures. The laying of engineering networks is provided, basically, in the form of above-ground infrastructure, while communications are located on overpasses; Corridors of communications are formed.

The total area of the territory that will be occupied for the construction of the complex for the extraction, preparation, liquefaction of gas, LNG and gas condensate shipment is estimated at 1,418,585 hectares, including 622,527 hectares taken on short-term lease (for the construction period), and 796,058 ha taken In the long-term (for the period of operation) lease.

In addition, a seaport will be built for the import / export of materials and equipment during the construction phase, as well as for export of received LNG and condensate at the stage of operation of the Project. When organizing the objects of the sea port, Yamal LNG will finance and be responsible only for the construction of berths for ships for unloading construction materials, LNG / condensate transportation, receiving terminals, communication systems, and office buildings in the port territory. Responsibility for work in the water area of the seaport, including dredging in the construction of the approach channel and on the coastal territory of the port, is borne by the federal authorities.

During the main phase of operation, the seaport will be used for the Project's purposes, but it will also be used by other organizations. The Federal State Unitary Enterprise for the Operation of Sea Ports "Rosmorport", which is founded by the Ministry of Transport of the Russian Federation and the Federal Agency for Sea and River Transport, will directly manage the seaport.

6. Ice Conditions in Russsian Arctic

6.1 Ice conditions on the tanker's route

In the Arctic seas, seasonal changes in ice conditions cause uneven volumes of sea traffic. Stable delivery of liquefied natural gas (LNG) from the Yamal Peninsula can be provided in two ways: by increasing the transport fleet and creating SPG stocks that can compensate for the irregularity of traffic. In this thesis, the methodology for calculating the optimal parameters of the transport and logistics system is described, depending on ice conditions.

Figure 5: Arctic sea ice extent for April 2017[5]

[5] National Snow and Ice Data Center https://nsidc.org/arcticseaicenews/

The key factor determining the intensity and the very possibility of LNG transport via the Arctic seas is the ice regime, i.e. the presence and state (extent, thickness and cohesion) of the ice cover. The design of the LNG plant in Yamal requires a detailed study of ice conditions in the adjacent water areas to calculate the parameters of the marine transport system. Transportation of LNG will be year-round, which provides for new criteria for assessing the complexity of navigation.

For seasonal navigation, the ice conditions are important only in the summer-autumn months. For the year-round - the main role is played by the winter-spring months, with the least favorable ice conditions.

The sea route to the Yamal peninsula (the Murmansk-Kharasavey route is considered as an example) passes through the southwestern part of the Russian Arctic, in the waters of the two seas - the southern part of the Barents Sea and the south-western part of the Kara Sea. The length of the route is 1200 km, including 850 km in the Barents Sea, and 350 km in Karskoe. Ice conditions in the Barents and Kara Seas are fundamentally different. In the Barents Sea, they are determined by the intensity of the sea currents, which bring a lot of warm water from the Atlantic Ocean. Due to this, a relatively favorable ice regime is observed in the Barents Sea, especially in its western part, which deteriorates as it moves eastward. The arrival of warm Atlantic waters with currents determines the shift in the seasonal maximum of ice conditions for the second half of winter (March-April). In the Kara Sea, the ice situation is determined by atmospheric conditions, primarily by the temperature regime[6].

6.2 Ice conditions in the Barents Sea

The route in the Barents Sea can be conditionally divided into three sections (from west to east), as the ice conditions worsen:

1. From the traverse of Murmansk to the traverse of. Kolguyev (450 km);
2. From the traverse of. Kolguev before the Kara Gates Strait (380 km);

[6] http://www.aari.ru/resources/m0001/ocean_summer/html/intro/intro_ks.htm

Strait of Kara Gates (30 km).
The first section is heavily influenced by warm currents. The ice regime is determined by the intensity of the influx of warm Atlantic waters. Ice occurs here about every second winter-spring navigation, usually in March-April, although in years with severe ice conditions, for example, 1999, ice fields are observed from January to May. The location of the ice edge and its cohesion are highly variable. Diluted young ice of local formation up to 30 cm in thickness predominates.

The second section of the route is characterized by the annual presence of ice, the average thickness of which increases from 30-50 cm in the west to 70-120 cm in the east. From the west, the waters of the Atlantic waters, strongly transformed, with a lowered temperature, enter the water area, and cold Kara water flows from the east, which flow along the southwestern coast of Novaya Zemlya in the form of the Litke current. The predominant one-year drift ice of local education prevails. The thickest ice in the east of the region comes from the Kara Sea.

The location of the ice edge is very variable - ice formation does not occur in some winters, ice fields occur only in the east, closer to the Karskie Vorota strait, where they come from the Kara Sea. On average, the presence of ice is observed from January to May, in years with severe ice conditions - from November to June. The Kara Gulf strait has the most difficult conditions for navigation due to the ice exchange with the Kara Sea. Annual ice drifts prevail, the thickness of which reaches 120-140 cm at the end of winter. In the strait, compression and hummocking of ice fields is often observed, which considerably complicates their overcoming. The presence of ice is typical from December to May, in certain years, from November to July. In the years with abnormally light ice conditions, for example, 2008, with stable western winds that exclude ice from the Kara Sea, the strait is covered with ice only for two months - March-April. In the area periodically observed one of the little-known phenomena, characteristic of the straits of the Arctic seas, the so-called ice river - the flow of ice drifting at high speed, capable of blocking the work of even nuclear icebreakers.

6.3 Ice conditions in the Karsk Sea

The route through the Kara Sea can also be divided into three sections, according to three types of ice phenomena:

- Novaya Zemlya ice massif (250 km);
- Yamal polynya (70 km);
- Fast ice off the coast of Yamal (20 km).

The Novaya Zemlya ice massif (NZM) is a vast accumulation of thick, annual ice of 8-10 points, localized between the Novaya Zemlya archipelago and the Yamal Peninsula. By the beginning of summer, NZM occupies about 60% of the water area, but by the end of August - beginning of September, as a rule, it disappears. In some years the massif remains during the entire summer-autumn period, and although considerably reduced in size, it can block the Kara Gulf strait for ice-free navigation. However, for the transport system, functioning year-round, overcoming NZM in the summer months will not cause difficulties.

Yamal polynya (YP) is formed between the ice massif and fast ice, due to the steady squeezing winds, driving away the ice from the edge of fast ice. In winter the polynyas freezes, representing a strip of young and relatively thin ice stretched from the north to the south. The fast ice forms a wide band of fixed ice off the coast of Yamal, which lasts most of the year - from November to July. By the end of winter, the thickness of fast ice off the western coast of the Yamal can reach 1 m. However, due to the stability of the fast ice, the navigable channel laid in it remains up to 4-5 days, which, with regular navigation, greatly simplifies the fast ice forcing.

There are western, central and eastern positions of NZM. In 70% of cases, the western position is observed, when the core of the massif is formed off the coast of Novaya Zemlya, and the southern spurs block the Kara Gulf Strait. In this case, the YP is formed in the eastern part of the sea, off the coast of Yamal.

At the eastern position of the NZM, the core of the massif is located in the eastern part of the sea, off the coast of Yamal, and the submontane polynya is formed in the west, off the coast of Novaya Zemlya. This location of the massif greatly facilitates the ice situation both in the straits leading to the Kara Sea and in the regions to the west of them. However, near the coast of Yamal, the ice situation is considerably more complicated, at the junction of the ice massif and fast ice there is considerable ice hummocking. In the central position of the massif, it occupies the central part of the water area, while the polynyas are irregularly formed on both sides of it.

6.4 Conditions for calculation of parameters of transport and logistic system

The position of the NZM, as well as the variability of the ice conditions in the Barents Sea, determine significant variations in the extent of the Arctic sections of the route. Significant differences are observed both in the months of the year and in the years. In March 1998 between Murmansk and Kharasavey there were 1200 km of ice, and in March 2008 - 400 km. Liquefied gas is not capable of storing for many years, therefore it is impossible to compensate for long-term fluctuations by the creation of reserves. With the accumulation of LNG reserves, only the annual (seasonal) fluctuations in the carrying capacity of the transport system can be compensated.

Therefore, the calculation of the parameters of the transport system, which is capable of ensuring the rhythm of supplies, must be carried out based on the conditions of the year with the heaviest ice conditions (the total length of the ice sections is 1200 km), rather than the average long-term ones. An exception may be extreme ice conditions, recurring exceptionally rarely.

The greatest expenditure of time is associated with overcoming the Novaya Zemlya ice massif and its spurs blocking the Kara Gulf Strait. This is the area with the thickest ice, the need to overcome it determines the necessary ice passage of the vessel (icebreakability 1.4 m, ice strengthening Arc7). The ice breakage of a ship is defined as the maximum thickness of the ice, which is overcome by the vessel in continuous motion with a minimum steady speed of 3.7 km / h (2 knots) * (1 knot = 1 nautical mile per hour = 1,852 km/h). In this case, the path through the Kara Gates (BM-3) and NZM in total will take more than 75 hours.

It is advisable to use a transport system with excessive ice permeability in order to increase the speed of movement through this section of the route. For example, at a speed of 7.4 km / h (4 knots), the time spent on this section will be halved to 38 hours, and the duration of the round trip (including loading and unloading) by 1/3, from 281 to 189 hours. Optimum speed selection Movement, the range of which lies, in all probability, in the range 7.4-11.1 km / h (4-6 knots), requires additional studies.

7. Simulation Model of the LNG Transportation

7.1 Data for Simulation

All sea units of measurements (miles and knots) were transferred by us to metric system. Also when calculating it was considered that one ton of LNG is equal to 1,380 m3 of gas.

According to official materials the general capacity of plant makes 16,5 million tons of gas a year that when converting gives us 22 770 million m3 a year. Therefore per day the plant produces 62,38 thous m3. Tonnage of the tanker (Arc7 "Christophe de Margerie") – 170 thousand m3 of LNG. Respectively a volume of gas sufficient for full filling of one tanker is made approximately for three days.

Also from this it is possible to draw a conclusion that the greatest possible number of shipments of gas – 121 in a year.

Today it is already made and one Yamal LNG intended for implementation of the project the tanker of the class Arc7 "Christophe De Margeri" passes tests.[7].

His declared high-speed characteristics:
- speed in open water - 19,5 knots; 36,11 km/h
- speed at the course in ices 1,5 meters thick - 5,0 knots; 9,26 km/h

We simply will take this speed for speed in ices in general

Distance between the ports of Sabetta (Yamal LNG Plant) and Zebryugge (The European basis of the project) makes 2800 miles (5185 km). From them on ice seasonally and an ice situation there pass from 400 to 1200 km. ways.

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[7] http://en.portnews.ru/news/236686/

Proceeding from the speed of the tanker and a distance on open water and on ices it is possible to allocate two extreme options of duration of delivery of gas:

- Optimistical option – 4785 km. + 400 km. = 132,5 hours + 43,1 hours = 175,6 hours = 7,3 days;
- Pessimistic option – 3985 km. + 1200 km. = 110,35 hours + 129,5 hours = 239,85 hours = 240 hours = 10 days.

Duration of a cycle of port service makes about 18 h. Respectively the cycle duration of operation of the tanker (gas loading, transportation to the port of destination, unloading, resetting to the plant) makes:
Optimistically 7,3 * 2 + 1,5 (18+18 hours in ports) = 16,1 days
21,5 days are pessimistic 10*2 + 1,5 = 21,5 days

7.2 Simulation Model Design

The model contains two processes:
- Gas production
- Gas transportation

Model run settings:
Since there is seasonality in our task (different travelling time) it is worth to look at each season separately and provide solution for the question, how many tankers are needed for each season. Thus, 92 days – number of days in one replication

7.2.1 Gas Production

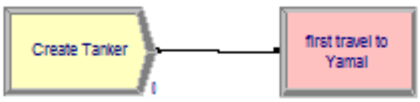
We consider that some amount of gas is produces in average every hour (1 entity per arrival appears with inter arrival time exponentially distributed: EXPO(1)). This amount will be equal in average 2600 m3. In order to get some stochastic for produced gas amount we will set value of Normal distribution: NORM (2600, 100). Total amount of gas, which was produced and has not been transported yet will be kept in variable: VGasAmount.

Figure 6: Scheme of Gas production Process

7.2.2 Gas transportation:

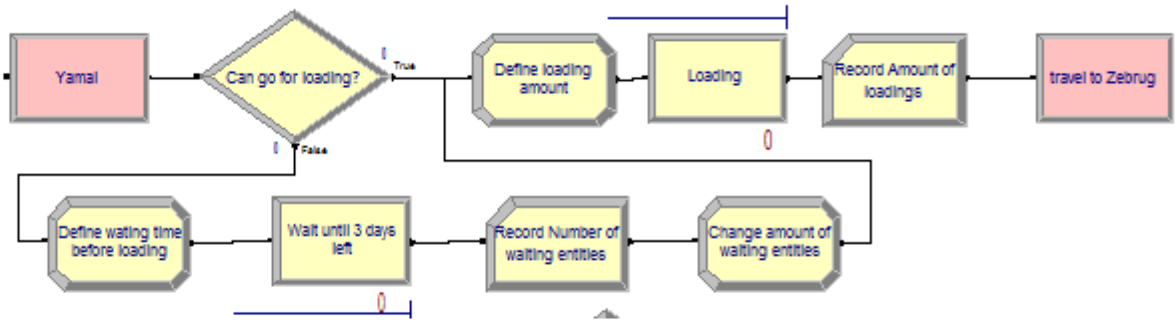
Firstly, tankers arrive every 3 days and have a shot travel to Yamal – in average 3 days (NORM(3,0.1)), with inter arrival time - exactly 3 days (we assume the tankers follow the schedule, that why do not use exponential distribution).

Figure 7: Scheme of Tanker Arrivals Process



When a tanker arrives to Yamal station, a decision about that, if the loading can be started, should be made. According our calculations, loading can be done not more often than every 3 days. That why the difference between last loading and current loading is compared with 3 days. With the help of the FALSE flow of DECIDE block "Can go for loading?" it can be understood, if the current amount of tankers, which we use is big (if a lot of tankers at the same time should wait at the same time for the loading, it means that amount of tankers used is big and some money are wasted useless). If time for the next loading came, loading starts and lasts 18 hours. On the tanker it is loaded or the whole amount of gas which was produced since the last loading, or the amount, which is equal tanker capacity. Then travelling to Zebrug starts.

Figure 8: Loading Decision Process



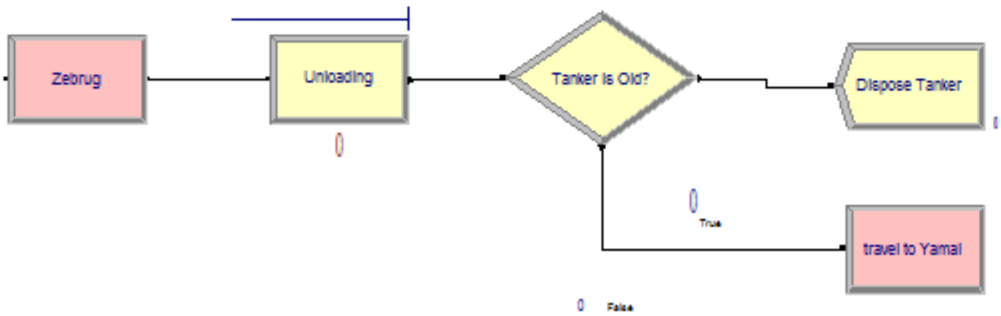
Time for travelling depends on the year season. We separate 3 different seasons: 1 – Winter, 2 – Spring, Autumn, 3 – Summer. We assume that travelling has Uniform distribution, where. For example, for Winter season the value will be: UNIF(9,10). For all other seasons the value can be find in the table of variable values: vTravelTime.

Figure 9: Table of variable values: vTravelTime.

	1	2
1	9	10
2	8	9
3	7.3	8

When the tanker arrives at Zebrug, Unloading for 18 hours starts and check of the tanker is made. If the tanker is old or needs repair, it goes to DISPOSE Tanker Block, otherwise it is going back to Yamal. Decision is made with the probability 0.001 of TRUE value (Tanker is old).

Figure 10: Unloading and Return Process



For an assessment of number of the taken place gas shipments we use the Unloading module. Respectively in this model result unloading of the tanker in Zebryugge and number of such operations for one replication is considered.
Completely the model is presented to Appendix I.

8. Experiment

For definition of optimum number of tankers when transporting we have carried out 24 replications of model with the different number of tankers (from 1 to 8) and various time of passing of a route, proceeding from season (3 options). The period of modeling made one calendar year or on one season "Summer" and "Winter" and two seasons "Spring-fall" (4 replications for 92 days). Results of an experiment are presented in table 1.

Table 1: Results of Imitation Model

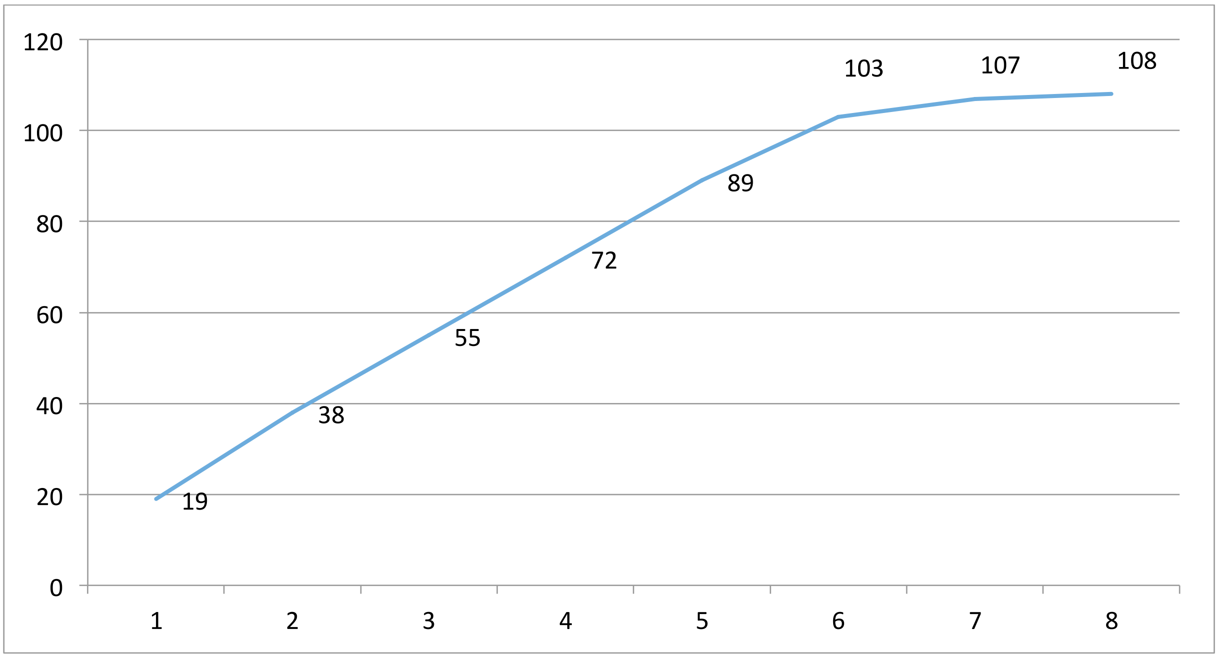
Number of Tankers	Winter	Spring	Summer	Autumn	**Total**
1	4	5	5	5	**19**
2	8	10	10	10	**38**
3	12	14	15	14	**55**
4	16	18	20	18	**72**
5	20	22	25	22	**89**
6	24	26	27	26	**103**
7	26	27	27	27	**107**
8	27	27	27	27	**108**

In process of increase in number of tankers the difference in number of the delivered consignments of gas at a different speed of passing of the ice site of a way becomes more notable. We see that the maximum number of the parties delivered in 3 months is equal 27 and it is caused by production capacities of the plant and the minimum time for passing of a route.

During the summer period the maximum number of deliveries is achievable already at 6 tankers. In winter time 8 courts are required. Similar seasonality can be optimized both due to use of gas storages, and due to diversification of deliveries (The Pacific Rim, the regions of the Northern Sea Route).

More visually additional usefulness of tankers is presented on Figure 11.

Figure 11: Dependence between Numbers of Shipments and Tankers



From the chart it is well visible that in process of increase in number of tankers their additional usefulness decreases. If the second tanker allows to increase number of the delivered consignments of gas on 19 in a year, then 8y the tanker adds only one party.

Respectively there is a question of profitability of use of additional tankers on a route. It is especially urgent taking into account that the cost of one tanker of the class Arc7 makes about 300 mln. dollars. Of course, in process of production and improvement of technologies their cost will fall. However anyway she will make hundreds of millions dollars, so to demand or considerable volumes of current assets of the project or borrowed funds that reduces profitability the project from need of service of the credits.

Proceeding from number of the delivered parties and also extreme usefulness of each additional unit of the fleet it is represented to us that optimum number of tankers for service of a route Sabetta – Zebryugge is 6. It will provide delivery of 103 consignments of gas in year or 17,5 million m3 of LNG. Thus, each tanker will make not less than 14 supply of LNG to Europe and it will provide payback of their construction.

Increase in number of tankers will be proved at increases in the output and diversification of deliveries through east part of the Northern Sea Route.

9. Conclusion and Suggestions for Further Research

9.1 Summary of the Conclusions

During this work we set the purpose to define optimum number of tankers for transportation of the liquefied gas produced within the project of Yamal LNG. For this purpose we have developed model which considered both production features of the LNG plant, and geographical conditions of transportation.

At the moment the problem of transportation of the volume of gas made by the Project can be optimum solved with use of 6 tankers. At the same time their construction and input in a system can take the long time depending on the cost of production, stability of financing of the Project and dynamics of the world prices for hydrocarbons.

As production and liquefaction of natural gas have no seasonal nature and are rather stable, an environment creates the main restriction on delivery with LNG from Yamal on the European and Asian sales markets. It is especially important if to consider that the peak of consumption of gas in Europe falls on the winter period when thickness of ice and time of his passing by the tanker are maximum.

Therefore when planning transportations it is important to consider seasonality of consumption and forecasts for an ice situation. The situation when tankers pass the ice site at the beginning of winter is optimum, and deliver gas to base by the time of the beginning of a cold snap I in Europe. The problem of distinctions in volumes of delivery and consumption can be also resolved due to construction of gas storages. Either at the plant, or in destinations (e.g. Zebryugge).

The option with diversification of deliveries not only to Europe, but also the Pacific Rim where gas generally provides requirements of production, but not heating is possible. Therefore seasonality of consumption isn't so expressed and it is possible to send the maximum volume of gas in the winter to the European region, and in the summer to Asia

9.2 Suggestions for Further Research

This work can gain the development in the following directions

1. Besides transportation of LNG from subpolar regions oil delivery as got in the territory of the Yamal Peninsula, so in the long term and from offshore platforms is carried out. These transportations can also be optimized due to creation of imitating models;
2. Modeling of supply of LNG to the countries of the Pacific Rim is possible;
3. In spite of the fact that the prices of hydrocarbons hardly give in to forecasting, and the ice situation in the Arctic significantly changes in process of global warming it is obviously possible to expand model at the expense of various scenarios of fuel prices and dynamics of change of an ice situation. The similar model will allow not only to define number of tankers from the point of view of the output, but also to define profitability of this project in various conditions.

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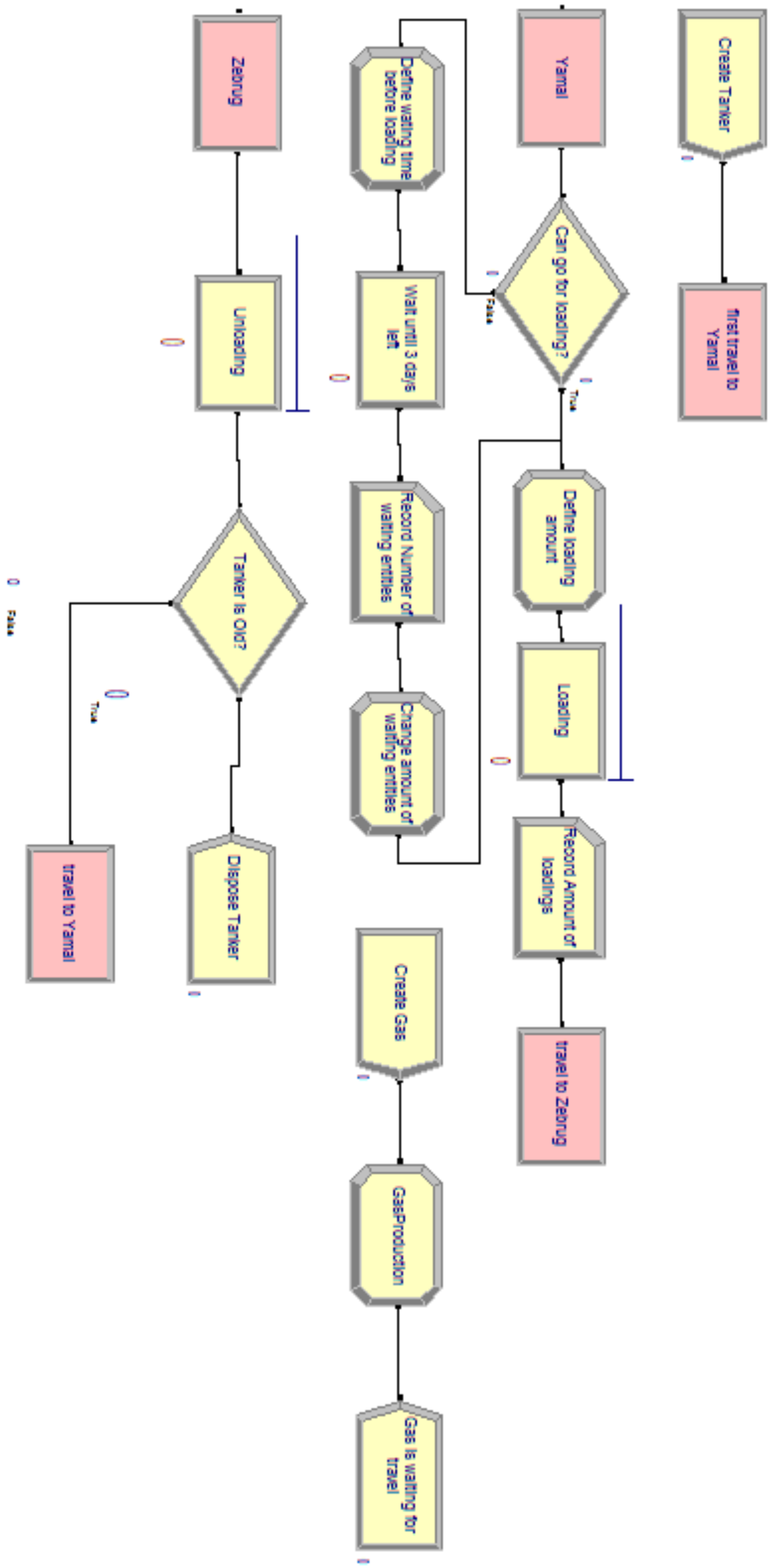
Appendix I: LNG Transportation Model



Appendix II: Replication Report

Yamal LNG

Replications: 1 Time Units: 92 Days

Key Performance Indicators

System

	Average
Number Out	2,230

Yamal LNG

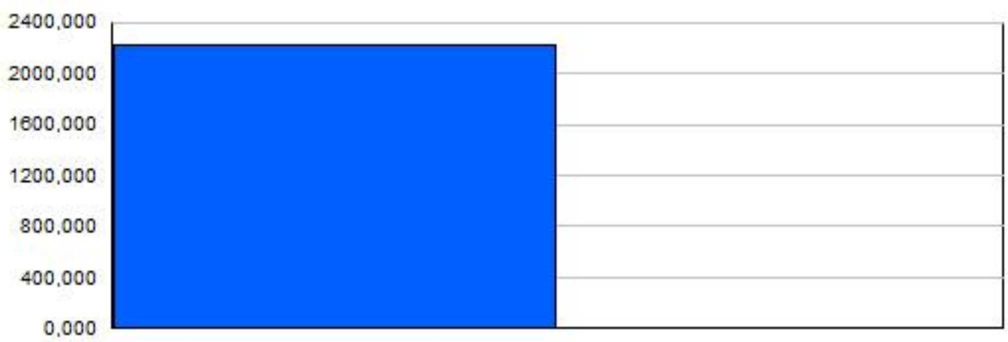
Replications: 1 Time Units: Days

Entity
Time

Other

Number In

	Value
Entity Gas	2230.00
Entity Tanker	6.0000



Number Out

	Value
Entity Gas	2230.00
Entity Tanker	0.00

Yamal LNG

Replications: 1 Time Units: Days

Entity

Other

WIP

	Average	Half Width	Minimum Value	Maximum Value
Entity Gas	0.00	(Insufficient)	0.00	1.0000
Entity Tanker	5.5109	(Insufficient)	0.00	6.0000

Queue

Time

Waiting Time

	Average	Half Width	Minimum Value	Maximum Value
Loading.Queue	0.00	(Insufficient)	0.00	0.00
Unloading.Queue	0.00	(Insufficient)	0.00	0.00

Other

Number Waiting

	Average	Half Width	Minimum Value	Maximum Value
Loading.Queue	0.00	(Insufficient)	0.00	0.00
Unloading.Queue	0.00	(Insufficient)	0.00	0.00

Yamal LNG

Replications: 1 Time Units: Days

Resource

Usage

Instantaneous Utilization

	Average	Half Width	Minimum Value	Maximum Value
GasLoader	0.2431	(Insufficient)	0.00	1.0000
GasUnloader	0.2200	(Insufficient)	0.00	1.0000

Number Busy

	Average	Half Width	Minimum Value	Maximum Value
GasLoader	0.2431	(Insufficient)	0.00	1.0000
GasUnloader	0.2200	(Insufficient)	0.00	1.0000

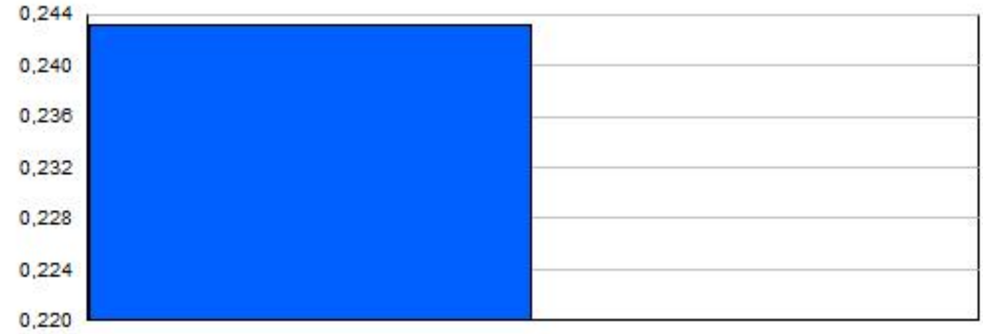
Number Scheduled

	Average	Half Width	Minimum Value	Maximum Value

GasLoader	1.0000	(Insufficient)	1.0000	1.0000
GasUnloader	1.0000	(Insufficient)	1.0000	1.0000

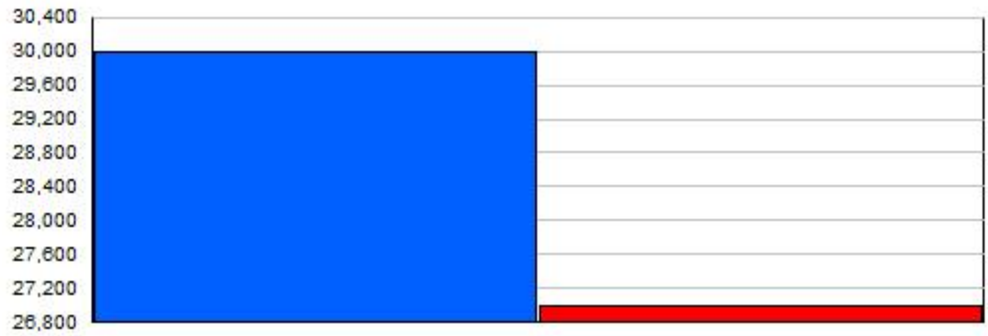
Scheduled Utilization

	Value
GasLoader	0.2431
GasUnloader	0.2200



Total Number Seized

	Value
GasLoader	30.0000
GasUnloader	27.0000



Yamal LNG

Replications: 1 Time Units: Days

User Specified

Tally

Expression	Average	Half Width	Minimum Value	Maximum Value
TallyDelay	1.0000	(Insufficient)	1.0000	1.0000

Counter

Count	Value
LoadingAmount	30.0000